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Dr. John Peoples Jr.
Director
FERMILAB, P.O. Box 500
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Dear John,

We are writing to express our intent to submit within a year a proposal to search for the muon neutrino magnetic moment down to 10^{-11} electron Bohr magneton (μ_B) level, using the Fermilab Booster proton synchrotron to produce a wide band muon neutrino beam.

The speculation that the electron neutrino might have a magnetic moment around the 10^{-10} μ_B level became a real possibility a few years ago when the Davis solar neutrino experiment reported data that indicated an anticorrelation between the neutrino capture rate and the number of sunspots. At that point a group of us started to study the different possibilities to search for neutrino magnetic moment in accelerator experiments. Since experiments that would use magnetic fields to flip the neutrino spin and look for a reduction in the weak cross section are practically impossible ($\int$BxdL of 100 kilometers x 30 KGauss would produce only a 1% effect for a 10^{-10} μ_B magnetic moment) we concluded that the way to search for neutrino magnetic moment is to look for deviations from the expected weak cross section in ν_μ e elastic scattering. The conclusions of our study are summarized in a paper (a copy of which we attach) that was submitted and will be published in the proceedings of the Breckenridge Workshop. The main conclusion was that sensitivities down to 10^{-11} μ_B level could be reached with a few years of running with the Booster after the Linac upgrade.

Last April more results were reported from the Davis solar neutrino experiment. They show a sharp drop in the solar neutrino flux - just as the present solar activity cycle approached its maximum. The significance of the results of this experiment has been greatly enhanced by a very recent report by the Soviet - American Gallium Experiment (SAGE) that confirms the deficit, relative to the theoretically expected value, in the number of the solar neutrino interactions detected on earth. We are very excited with these developments. The importance as well as the implications, to both physics and cosmology, of a discovery that the neutrino has magnetic moment cannot, of course, be overstated.

We would appreciate your communicating our letter of intent to the Fermilab Physics Advisory Committee.

Sincerely,

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SEARCH FOR THE MUON NEUTRINO MAGNETIC MOMENT AT THE 10^{-10} BOHR MAGNETON LEVEL USING THE BOOSTER AT FERMILAB

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Abstract

We review the experimental and theoretical limits on the neutrino magnetic moment. We examine the possibility of doing a muon neutrino magnetic moment search down to 10^{-10} to 10^{-11} Bohr magneton level using the Booster accelerator at Fermilab. A possible secondary beam and detector configuration is outlined.

1. INTRODUCTION

The interaction of the neutrino magnetic moment μ and the electromagnetic field $F_{\mu\nu}$ is described by the following Lagrangian term[1]:

$$\mathcal{L}_{int} = \frac{1}{2}\overline{\nu}_R \sigma_{\mu\nu} \nu_L F_{\mu\nu} - h.c. \tag{1}$$

In standard $SU(2)_L \times U(1)$ theory the neutrino has a magnetic moment induced by radiative corrections and proportional to the neutrino mass m_ν[2,3]:

$$\mu = \frac{3eG}{8\sqrt{2}\pi^2} m_\nu = \frac{3m_e G}{4\sqrt{2}\pi^2}\mu_B m_\nu \approx 2.7 \times 10^{-10}\mu_B \frac{m_\nu}{m_N}, \tag{2}$$

where G is the Fermi constant, μ_B is the Bohr magneton ($\mu_B = e\hbar/2m_e c$) and m_N is the nucleon mass. The magnetic moment, described by the above formula is very small, for example neutrino with mass $m_\nu = 30$ eV has the magnetic moment $\mu \approx 10^{-17}\mu_B$.

We will now review the limits on μ that follow from reactor experiments and astrophysical estimates. The interaction (1) produces an additional contribution to the neutrino-electron scattering cross section described by Feynman diagram of Figure 1.

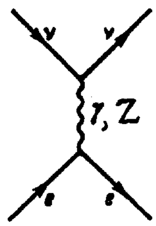

Figure 1. Feynman diagram showing the neutrino-electron scattering due to the exchange of a Z (weak neutral current) or a photon (electromagnetic part due to the neutrino magnetic moment).

The differential cross section for νe scattering due to the neutrino magnetic moment is given by[4]:

$$\frac{d\sigma_{em}}{dT} = \frac{\mu^2}{\mu_B^2}\frac{\pi\alpha^2}{m_e{}^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right), \tag{3}$$

where E_ν is the energy of the incident neutrino and T the kinetic energy of the recoil electron. This is to be compared with the following expression for the differential cross section due to the weak neutral current[5]:

$$\frac{d\sigma_W}{dT} = \frac{G^2 m_e}{2\pi}\left[(1 - \frac{T}{E_\nu})^2(1 + 2\sin^2\theta_W)^2 - 4\sin^4\theta_W - (1 + 2\sin^2\theta_W\frac{m_e T}{E_\nu^2}\right], \tag{4}$$

where θ_W is the Weinberg angle. The electromagnetic and weak amplitudes do not interfere, because the final states are different for the two cases (the final state neutrino helicities are opposite), so that the total cross section is the sum of the expression given by (3) and (4). When $T \ll E_\nu$, the cross section given by (4) becomes constant, while that in (3) behaves as T^{-1} and for $\sin^2\theta_W = 0.22$ and $\mu \approx 10^{-10}\mu_B$ it becomes comparable with the weak cross section at $T = 0.3$ MeV. The experimental data reported in Ref. 6 have been used to show that for the electron neutrino $\mu \leq 2 \times 10^{-10}\mu_B$. Astrophysical limits on μ have been obtained (see Ref. 1 and Refs therein) by considering the cooling of young white dwarfs due to the decay of plasmons to $\nu\bar{\nu}$ pairs. Analysis of astrophysical data gives $\mu \leq 0.7 \times 10^{-10}\mu_B$.

The possibility that the electron neutrino could have a magnetic moment around $10^{-10}\mu_B$ was enhanced with the new information provided by the solar neutrino experiment[7]. It is well-known that the average neutrino capture rate is almost three times smaller than the value predicted in the standard solar model[8]. Even more interesting is that the solar-neutrino data indicate an anticorrelation between the neutrino capture rate and the sun-spot number[9]. An explanation has been proposed in Ref. 1. It is suggested that this anticorrelation could be explained if the electron neutrino had a magnetic moment of the order of $10^{-10}\mu_B$. The $B \cdot L$ required to turn the spin through an angle of the order of unity is given by

$$B \cdot L \sim \mu^{-1} \approx 3 \times 10^{13} \mathrm{G\,cm}. \tag{5}$$

Since the thickness of the convective zone of the sun is $L \approx 2 \times 10^{10}$cm, from Eq.(5) the magnetic field needed is $B \approx 1.5 \times 10^{3}$G. This value is consistent with what is believed to be the strength of the magnetic field in the sun's convective zone. We pointed out earlier that the Standard Model prediction for the magnetic moment of a neutrino with mass 30 eV is $\sim 10^{-17}\mu_B$ (see Eq.(2)). A value of $10^{-10}\mu_B$, as suggested by the solar neutrino experiment, could be explained by the introduction of right handed currents[1] or by simple extensions[10,11,12] of the Standard Model which lead to a large transition magnetic moment of the electron neutrino while keeping the neutrino mass naturally small. This model can provide a solution to the solar neutrino puzzle while at the same time avoiding the SN1987A bound on the neutrino magnetic moment.

Irrespective of theoretical prejudices we think that the data of the solar neutrino experiment provide a strong hint that the magnetic moment of the electron neutrino could be $10^{-10}\mu_B$. If the anticorrelation between the number of solar spots and the number of neutrino interactions is observed again during the next solar activity maximum (expected to take place during the next year) the significance of the earlier observation will be greatly enhanced. Since the discovery of neutrino magnetic moment would strongly suggest that the neutrino also has mass with further consequences on both particle physics and cosmology we feel that an accelerator search for it will be justifiable. The most suitable accelerators for this purpose are those that can provide high intensity, low energy neutrino beams. In the following Section we examine the feasibility of doing a muon neutrino magnetic moment search at Fermilab's Booster accelerator.

2. MUON NEUTRINO MAGNETIC MOMENT SEARCH AT THE FERMILAB'S BOOSTER

The best experimental limit on the muon neutrino magnetic moment comes from Brookhaven experiment E734 a study of $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$. It gives a limit[13] of $0.85\times 10^{-9}\mu_B$. The astrophysical limit[14] (for $m_{\nu_\mu} < 10$ keV) is $8.5\times 10^{-11}\mu_B$.

In order to examine the feasibility of doing a muon neutrino magnetic moment search at Fermilab's booster to at least one order of magnitude higher level than Brookhaven E734 we have run the NUADA[15] program with the pion production spectrum of Ref.16. Taking the incident proton energy to be 8 GeV using a single MORI-type horn, a pion decay length of ~ 15 meters, the muon neutrino flux 5 meters behind a 7 meter concrete dump is found to be 2×10^{10} per 10^{13} protons over a 4 m^2 area detector (2 m$\times$2 m). Since, after the Linac upgrade,[17,18] the booster will be able to provide 3×10^{13} protons/sec this means that a total neutrino flux of

6×10^{10}/sec over a detector of 2 m$\times$2 m could be achieved. This is to be compared with 10^{10} neutrinos/sec at BNL E734. We further take our detector to be a 2 m$\times$2 m (area), two 5 m long water tanks with complete photomultiplier coverage on their back surface. Such a detector contains 3.2×10^{26} target electrons/cm^2. Since the electron threshold energy in water is 0.26 MeV we have integrated Eqn. (3) from a T_{min} of 1 MeV to $T_{max} = 100$ MeV to get a total $\sigma_{EM} = 1.24 \times 10^{-44}$ cm^2 (for a muon neutrino magnetic moment of $10^{-10}\mu_B$). Putting all the numbers together we get an electromagnetic rate of $\sim$ 8 per year. We conclude that a search of muon neutrino magnetic moment down to $10^{-10}\mu_B$ is possible. $10^{-11}\mu_B$ level could be feasible if the booster intensity could be increased by a factor of 5. This, for example, might be achieved if the Booster cycles at the nominal 15 Hz and if its intensity could be pushed to its space charge limit.

Work is at present underwav on the following subjects:

i) Setting up a Monte Carlo for detector simulation of both background and signals of physics of interest, and

ii) Using the NUADA program to optimize (as far as signal *vs.* background is concerned) the incident proton energy.

At the same time we are anxiously awaiting the coming of the next solar activity maximum!

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